

TWO-PHASE ANNULAR FLOW IN HELICAL COIL FLOW CHANNELS IN A REDUCED GRAVITY ENVIRONMENT

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ABSTRACT

A brief review of both single- and two-phase flow studies in curved and coiled flow geometries is first presented. Some of the complexities of two-phase liquid-vapor flow in curved and coiled geometries are discussed, and serve as an introduction to the advantages of observing such flows under a low-gravity environment. The studies proposed -- annular two-phase air-water flow in helical coil flow channels are described. Objectives of the studies are summarized.

INTRODUCTION

Two-phase liquid/vapor flow occurs in a wide variety of earth applications ranging across the petrochemical, power generation, refrigeration, and aerospace industries. A greater understanding of multiphase systems and flows would be of great practical benefit in terms of the improved design methodology that could be applied to such systems. Even though two-phase flows have been studied extensively under earth gravity conditions, the accuracy of the multiphase predictive and design tools is poor compared to those available for single-phase systems.

The presence of an earth gravitational environment can enormously complicate a two-phase liquid/vapor flow, resulting in a variety of perturbations, instabilities and generally undesirable unsteady features.

The orientation of the flow channel (e.g. horizontal versus vertical) can dramatically change the behavior and characteristics of a two-phase flow in a 1-g environment, contributing further to the difficulty of obtaining an fundamental understanding of two-phase liquid/vapor flow dynamics. Studying two-phase flow systems a low-gravity, or microgravity environment can remove such undesirable, masking flow complications which occur under earth gravity conditions.

Additionally, however, two-phase flow in microgravity conditions occurs in a variety of space system applications. Examples include the transfer of cryogenic fluids, cooling of electronic components, and heat pipe applications. Future applications include the design of the space station components and systems. Consequently, an understanding of two-phase flow under microgravity conditions is necessary to insure accurate design and reliable operation of future space systems.

LITERATURE REVIEW

Single Phase Flow

As early as 1927 Dean [1] made a theoretical study of fully developed laminar flow in a curved pipe. He pointed out the existence of a secondary flow set up by the centrifugal forces in the curved geometry (see Fig. 1-(a)). His considerations of dynamic similarity resulted in a parameter $K = Re(r/R)^{1/2}$ (which is now called the Dean number), where r and R are the tube and coil radii, respectively.

In 1965 and 1967 Mori and Nakayama [2,3] performed an analysis of both fully developed laminar and turbulent flow in curved pipes. Using an approach analogous to that resulting in the Reynolds stress in turbulent flow analyses, they developed a relation between the secondary flow velocities and the stresses caused by the secondary flow. Their analytically obtained formulas for f_s/f_s , for both laminar and turbulent flow agreed well with their experimental results, lending credence to the idea that additional flow resistance in curved geometries is caused by stresses due to secondary flow. Further, the secondary flows caused by centrifugal forces have a stabilizing effect on laminar fluid flow, and delay the transition to turbulence.

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Ito [4] developed an empirical equation to describe the influence of the ratio of the tube and coil diameters upon the (delayed) transition to turbulent flow. Srinivasan [5] presented an improved empirical equation for the critical Reynolds number, which agrees well with experimental results.

Hart et al [6] proposed an expression for the friction factor of a coiled flow channel as a multiple of that in a straight tube, in terms of the Dean number, for laminar flow, as follows:

$$f_c = f_s \{ 1 + [0.090 De^{1.5} / (70 + De)] \}$$

where $f_s = 16/Re$, and valid for $Re < Re_{crit}$, and where $Re_{crit} = 2100[1 + 12(d/D)^{1/2}]$.

For turbulent flow, White [7], Ito [4], Srinivasan [5] and Mishra [8] have proposed expressions for friction factors for flow in coiled geometries that yield similarly good agreement with experimental results in their applicable ranges. By combining equations proposed for the laminar and turbulent domains, Hart et al [6] introduced a friction factor chart for single-phase fluid flow through curved tubes or helical coils, as presented in Figure 2.

Two-Phase Flow

Relatively fewer studies of two-phase flows in curved or coiled geometries have occurred. Some of the earliest studies of such flows were by Owhadi, Bell & Crain [9-10], and Banerjee et al [11]. Initially, it was hypothesized that for annular two-phase flow in helically coiled tubes, the induced centrifugal forces should force the liquid onto the outside wall (see Fig. 1-(b)). However, Owhadi et al [9] indicated that his hypothesis was inaccurate since they obtained higher dryout qualities with the coiled tubes than those normally found in straight tubes. Based on these findings, Owhadi et al [9], Banerjee et al [11], and Crain et al [10] hypothesized that secondary flow similar to that shown in Fig. 1-(c) should exist in the gas core of an annular two-phase flow in a helically coiled tube.

For some high quality flows in helical coils, Banerjee [11] reported that at low liquid flow rates, but high gas flow rates, the liquid phase travels along the inside of the tube wall (nearest the coil axis), rather than on the outside wall as might be expected due to centrifugal forces. In other words, a film inversion was observed to occur under some flow conditions, typically of high vapor phase velocity and low liquid phase flow rates.

A more recent study is that of Uddin [12], who developed a model to predict two-phase flow patterns in helically coiled tubes. More recent studies by Yan [13] showed an apparent inadequacy of this map, based upon her studies of air-water and R-12 flow pattern and pressure drop characteristics in upward flows in vertically oriented helical coils of square, rectangular and circular cross-sections. Yan developed a frictional pressure drop correlation for the R-12 flows.

In another relatively recent study Saxena et al [14] studied flow patterns, holdup and pressure drop for air-water flows in vertically oriented helical coils, for upward and downward flows. A model was proposed to predict pressure drop for both upward and downward flows. Most recently, Awwad et al [15] studied flow patterns and pressure drop in air-water flows in horizontally oriented helical coils. They proposed frictional pressure drop multipliers based upon both the Lockhart-Martinelli parameter and the flow rates.

Microgravity Two-Phase Flow

A rather limited number of studies of two-phase flows have been conducted under low- or micro-gravity conditions. Among the earliest studies were those of Williams et al [16], Keshock et al [17], and Hepner et al [18]. In [16] and [17] flow pattern observations were made of the flow condensation of R-12 in a 2.62 mm dia. x 1.83 m long tube. Hepner et al [18] observed flow patterns and made pressure drop

measurements for air/water flow in a 2.54 cm dia. tube with a length to diameter ratio of only 20. All of these studies were conducted using KC-135 flights to obtain the low-gravity condition.

Dukler et al [19] made flow pattern observations and limited pressure drop measurements of air/water two-phase flow in a 1.27 cm dia. x 1.06 m test section ($L/D = 83$), using a Learjet aircraft. Their principal result was the development of a flow pattern map based upon modeling of the observed flow patterns and their transitions.

Chen et al [20-21] also made flow pattern observations and obtained the most extensive pressure drop data obtained to that time for two-phase R-114 flow in a 1.58 cm dia. x 1.83 m straight tube ($L/D = 116$). A KC-135 aircraft was used to create the low-gravity condition. The measurements were compared with several existing correlations for predicting two-phase pressure drop. The principal result was the development of a new correlation for the prediction of pressure drops in a reduced gravity environment, based upon an annular flow model and using an interfacial friction factor developed from the data [21]. Also, their flow pattern observations were used to modify the Dukler map [20]. (The foregoing studies are representative of the studies of two-phase flow that have been conducted under microgravity conditions. They are not intended to be a totally comprehensive review of such studies, due to restrictions on article length.)

PROPOSED MICROGRAVITY STUDIES

In the study of two-phase flows, one of the most important measurements and characteristics of interest is that of the pressure drop, whether under 1-g or reduced gravity conditions. However, the length of straight channel required to make accurate pressure drop measurements is relatively large. These length requirements are prohibitive, considering the spatial and geometric restrictions associated with facilities designed for the attainment of low-g environments, e.g. drop towers and aircraft. Consequently, a need exists for accurate and plentiful measurements of two-phase pressure drop for microgravity conditions. The use of a coil geometry in combination with a low-gravity environment offers an opportunity to obtain such accurate measurements, since the physical impediment of inadequate length can be eliminated.

The second major characteristic of interest in two-phase flows is that of the details of the distribution of the phases (i.e. flow patterns), and the transitions from one type of flow pattern to another. In the proposed study, the slug-annular transition will be focused upon, though with the long channel lengths possible in a coiled geometry, the "development" of bubble and slug flows can also be observed.

In the near absence of gravity, the enormous complications in a two-phase flow field created by our normal 1-g earth environment disappear. Instead, the only force akin to a gravitational force would be the centrifugal forces acting on the fluids owing to their centripetal acceleration through the curved flow passage. In effect, the two-phase flow in the extended length of coiled flow channel would be occurring in a fractional gravitational field, directed toward the outer radius of the coil.

It should be observed that the coiled flow path would induce secondary flows within the fluid(s) that are not present in a straight-channel geometry. However, the magnitude of such secondary flows diminishes with larger coil radii, and with smaller fluid velocities; Accordingly, their magnitude can be controlled to some extent by the experimental design. Furthermore, their influence could be established and quantified in comparative tests of straight and coiled channel geometries in ground-based laboratory tests, and perhaps also in aircraft flight tests.

With such comparative tests, a coiled geometry makes it possible to make fundamental measurements and observations of annular two-phase flows in a flow channel of considerable length, such as pressure drop, related interfacial characteristics, and conditions relating to the slug-annular flow regime transition.

EXPERIMENTAL APPROACH

Only the adiabatic flow of air/water will be studied. Tests will initially be conducted under earth-gravity conditions, i.e. in a conventional test cell. Tests will then be conducted using the low-g environment possible using a DC-9 aircraft, which is capable of providing low-g test intervals of 22 second duration.

It is planned to study flow in both transparent flexible plastic tubing and lengths of stainless steel tubing, all of 3/4" diameter, wound into a helical coil shape of 20" diameter. One 20-ft stainless steel coil will be employed in ground tests to compare with pressure drop measurements in a straight length of 20-ft tubing of the same diameter. Aircraft tests will employ a stainless steel coil of 40-ft length ($L/D = 640$) to insure the most accurate measurement of pressure drop.

Both ground and aircraft tests will utilize a 40' length of 3/4" I.D. flexible transparent tubing wound in a 20" diameter coil to provide accompanying flow visualization information. The test sections will be adapted for installation on an existing two-phase test rig developed specifically for aircraft flight testing.

PROJECT OBJECTIVES

The primary experimental objectives of the proposed study will be to make (1) accurate measurements of pressure drop and (2) video/photographic observations of details of the two-phase flow dynamics, while operating in a microgravity environment.

In addition to the measurement of two-phase pressure drops, desired measurements to be sought are those of (1) Taylor bubble length, (2) liquid slug length, (3) slugging frequency, (4) bubble size and distribution. Measurements of liquid film thickness and void fraction are not feasible within the coil length, but only in the straight lengths preceding and following the coil.

The primary technical objectives are to:

- (1) Make a comparison/validation study of coil measurements and observations with respect to straight channel flows under 1-g and reduced gravity conditions.
- (2) Use the quantitative and observational data to evaluate the accuracy and validity of two-phase flow maps in predicting two-phase flow regimes and their transitions, especially generalized maps such as developed in [22], where the slug-annular transition is predicted over the entire range of accelerations vectors and magnitudes from earth gravity to microgravity conditions.
- (3) Use the data and observations to evaluate and improve upon the accuracy of two-phase pressure drop correlations in predicting pressure drops for the modified flow patterns associated with low-gravity and microgravity environments.
- (4) Provide data to be used as a basis of understanding for the definition of future flight experiments, ultimately leading to a sound fundamental understanding of two-phase fluid physics.

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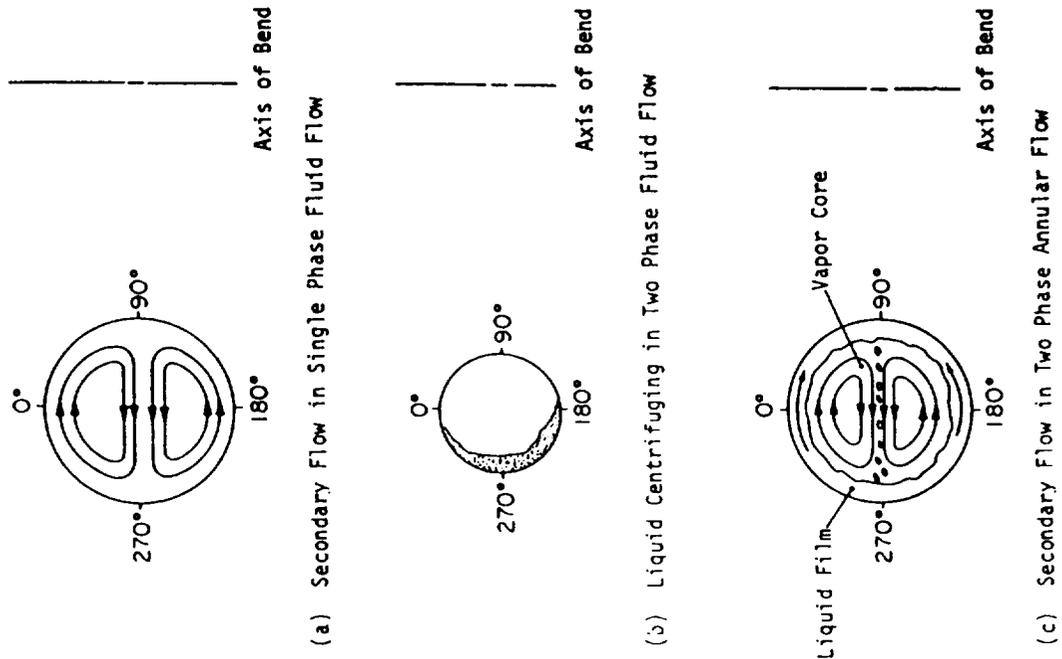


Figure 1. Secondary Flow in Coiled Tubes

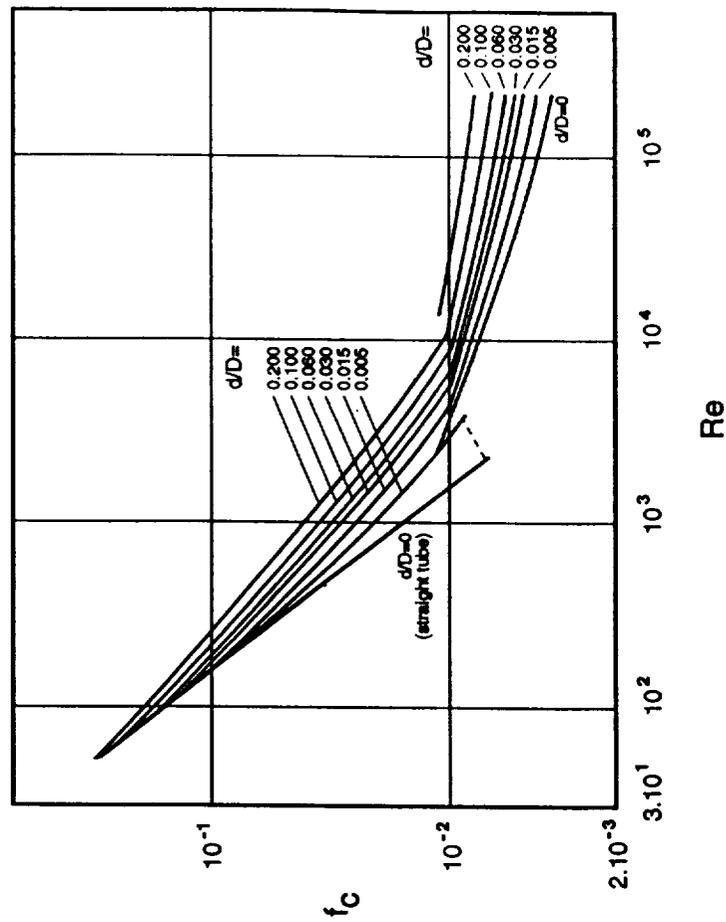


Figure 2. Friction factors for straight tubes and curved or helically coiled tubes (after Hart et al [6]).